Hydrogen production system from photovoltaic panels: experimental characterization and size optimization

M.L. Ferrari, M. Rivarolo , A.F. Massardo

TPG, University of Genoa -TPG, Via Montallegro 1, 16145 Genoa, (Italy)

Corresponding author: mario.ferrari@unige.it
Tel. +39 0103532443

ABSTRACT

In this paper an approach for the determination of the optimal size and management of a plant for hydrogen production from renewable source (photovoltaic panels) is presented.

Hydrogen is produced by a pressurized alkaline electrolyser (42 kW) installed at the University Campus of Savona (Italy) in 2014 and fed by electrical energy produced by photovoltaic panels. Experimental tests have been carried out in order to analyze the performance curve of the electrolyser in different operative conditions, investigating the influence of the different parameters on the efficiency. The results have been implemented in a software tool in order to describe the behavior of the systems in off-design conditions.

Since the electrical energy produced by photovoltaic panels and used to feed the electrolyser is strongly variable because of the random nature of the solar irradiance, a time-dependent hierarchical thermo-economic analysis is carried out to evaluate both the optimal size and the management approach related to the system, considering a fixed size of 1 MW for the photovoltaic panels. The thermo-economic analysis is performed with the software tool W-ECoMP, developed by the authors' research group: the Italian energy scenario is considered, investigating the impact of electricity cost on the results as well.

Keywords: renewable energy sources, thermo-economic optimization, hydrogen production.

NOMENCLATURE

Abbreviation

AEC	Alkaline Electrolytic Cell
CCS	Carbon Capture and Sequestration
DPBP	Discounted Pay Back Period
IRR	Internal Rate of Return
NPV	Net Present Value
PEC	Purchased Equipment Cost
TCI	Total Capital Investment
TPG	Thermochemical Power Group
W-ECoMP	Web-based Economic Cogeneration Modular Program

Symbols

C	Cost [€]
F	Faraday constant [C/mol]
HHV	High Heating Value [MJ/kg]
I	current [A]
M	mass flow rate [kg/h]
P	power [kW]
p	pressure [Pa]
Q	flow rate [m^3/s]
R	gas constant [J/kg K]
T	temperature [K]
V	voltage [V]

Subscripts

0	*standard conditions*
f	fuel
fix	fixed
inst	installed
rev	reversible

Greek symbols

η	efficiency
ρ	density [kg/m^3]

1. Introduction

The issues related to environmental rules defined in the last years has moved researchers to increase the interest in innovative fuels able to produce low (or zero) emission conditions. In this scenario, hydrogen is considered interesting because it is a fuel able to avoid any CO_2 emission during combustion [1]. However, since hydrogen is not a natural fuel, it is necessary to produce it throughout chemical, electrochemical or different approaches. An interesting option for its production is water electrolysis employing electricity from renewable sources [2][3]. Since renewable sources can produce significant uncontrollable variations during generation, the electrical energy total available amount can be significantly higher than the demand values during peak production. Considering these aspects, an interesting solution is related to hydrogen production (using the exceeding energy) performing a sort of chemical electricity storage. The produced hydrogen flow can be used for electrical energy generation at high efficiency conditions toward fuel cells and hybrid systems [4]. Even if previous works were carried out on hydrogen generation from renewable sources considering electrolysers [5][6][6], usually just nominal performance data are available for these kinds of reactors. So, in this paper the problem was started from a wide experimental campaign producing electrolyser off-design data not published by manufacturers' communication documents. Hydrogen generation from renewable sources and the related storage/utilization aspects (considering both efficiency and cost issues) have to be considered starting from calculations [8][9]. Even if several optimization tools were applied at different cases [8][9] (both conventional or advanced methods [10][11][12][13][14]) an experimental support is essential for defining real optimized size and management for real plant applications. So, in this paper a real test case (considering the experimental electrolyser curves) was carried out on solar power source referred to the campus located in Savona (geographical coordinates: 44°18’28.71”N 8°28’51.66”E), Italy.

The Italian generation related to renewable sources is close to 112 TWh: even if the largest amount (52.7 TWh) is produced by hydroelectric plants, the impact of other renewable sources has significantly increased. Considering the generation based on renewable sources related in 2000 [15], a strong increase can be highlighted (from 51 TWh to 112 TWh), mainly for solar energy system installations (+21.6 TWh), wind power plants (+14.3 TWh) and biogas/biomass based systems (+15.6 TWh), while generation by hydroelectric and geothermal are almost constant. Among the renewable source based plants installed in Italy, 591,029 systems are photovoltaic plants [15]. They represent a significant number in comparison with wind power plants (1,386), hydroelectric systems (3,250) and biogas/biomass power plants (2,409). So, considering these aspects related to the Italian scenario, photovoltaic technology was taken into account as renewable source based electrical input for the hydrogen generation evaluated in this paper.

The results presented in this paper were obtained in the Research Project named ***IDRO-RIN TRAN-GENESI*** and by the Italian government. It was related to development of innovative technologies for hydrogen generation from renewable sources (large size plants) and the utilization of this fuel in both land and naval transportations. The main topics related to this project, presented in Fig. 1, were: (i) H_2 production from renewable sources using water electrolysis [16][17]; (ii) H_2 storage devices and management considering both traditional and innovative approaches; (iii) hydro-methane generation from H_2 and CO_2 from biomass gasification or Carbon Capture and Sequestration (CCS); (iv) thermo-economic optimization of plants for generation of hydrogen and hydro-methane, storage systems and utilization devices, considering the availability aspects and the economic conditions.

Figure 1

In this paper, the experimental results of the test campaign performed on the alkaline electrolyser installed at the University of Genoa campus in Savona are presented and discussed, investigating the influence of the different parameters on the performance. In the test campaign, the electrolyser is fed by electricity from the national grid and the performance of the device at different load conditions is evaluated. Then, a thermo-economic analysis is carried out, considering to feed the electrolyser by time-dependent renewable energy, provided by photovoltaic panels, eventually purchasing electrical energy from national grid when solar energy is not sufficient. The thermo-economic analysis is performed considering the real irradiance curves of Savona and using the in-house software **W-ECoMP** (Web-based Economic Cogeneration Modular

Program) for system optimization to define the optimal plant size and the best management approach for the electrolyser, minimizing costs as well.

2. Plant Layout

The plant considered in this work is an experimental facility developed to operate tests on electrolysers. It is a simple test bench (Fig. 2) able to measure electrolyser main properties (voltage, current, temperature) and hydrogen flow characteristics (pressure, temperature and mass flow rate). All the probes have a ±1% accuracy, except temperature sensors which are affected by a ±0.3 K accuracy performance. The rig is also equipped with outlet valves on both hydrogen and oxygen sides to operate pressurised tests. Moreover, a dryer was installed on the hydrogen line to avoid water drops inside the mass flow rate probe. While oxygen produced by the electrolyser is simply vented, hydrogen is burned in a torch (see Fig. 2).

Figure 2

2.1 Electrolyser

The electrolyser (Fig. 3) tested in this work is the Piel "DODICIMILA" device (since now the production has been changed, the most similar device is sown in**Error! Reference source not found.** as S12MP) able to produce up to 8 Nm^3/h of hydrogen at 99.5% pureness. It is an alkaline electrolyser (AEC) with two stacks connected in series to a current rectifier (from three phase 50 Hz current). The gases (hydrogen and oxygen) produced from demineralised water are stored into two different vessels located inside the device case and connected to the delivery ducts. These tanks are necessary to separate the gases from the liquid containing the electrolyte: the gases are stored in the upper part, while the liquid is recirculated to the stacks from the lower part of these tanks. Moreover, an equalizer device is installed to have equal pressure values (and equal liquid level in the vessels) in both hydrogen and oxygen sides and a second device is present to avoid cell damage in case of not equalized outlet flow rates (oxygen volume flow rate has to be the half of the same property for hydrogen). The correct balance is obtained discharging a part of one of the produced flows (oxygen or hydrogen) to a venting duct. A fan cooler is included to maintain the electrolyte temperature lower than 65°C (338.15 K) toward a water flow used to remove heat from the recirculated liquid flow. Moreover, both gas lines are cooled with a fan and are equipped with the following instruments: condensate separation devices, manometers and valves to prevent flame return in case of gas ignition.

Figure 3

This electrolyser is also equipped with probes for control reasons and fault management. In details, the machine includes the measurement devices for gas pressure, electrolyte temperature, liquid level in the tanks and electrical current. All these sensors are connected to the control unit able to manage the current [19] depending on the gas demand, control (towards an on/off pump) the new water feeding (from an external tank), and start the fan for electrolyte cooling. To complete this description Tab.1 shows the main technical data related to this electrolyser.

Table 1

3. Experimental Tests

Several experimental tests were carried out on this electrolyser **Error! Reference source not found.** installed in the test bench in the "Innovative Energy Systems Laboratory" by TPG, planning possible future applications for alternative fuel analysis (mixing hydrogen with natural gas for existing plants [20][21] after modifications on the combustion systems). The objective of this experimental campaign was related to the generation of experimental curves to be implemented in the electrolyser tool of W-ECoMP software [22][23][24], as shown in the next paper section. This new tool will be essential for optimization management [25] of innovative systems based on hydrogen generation from renewable sources [26][27][28]. In the experimental campaign, energy to feed the electrolyser is provided by the national electrical grid, in order to control the off-design conditions and better evaluate the influence of some parameters (i.e. current) on the performance.

An initial plot (Fig. 4) related to this experimental campaign is the characteristic curve (voltage versus current) of the electrolyser stack at constant pressure condition. In this case both stacks were at 2.4 bar. The trend is almost linear except the low current condition usually affected by activation losses [29].

$$\eta = \frac{HHV \cdot \rho_0 \cdot Q}{3600 \cdot V \cdot I} \quad (1)$$

Figure 4

This almost linear trend is also present in Fig. 5 for the efficiency of the electrolyser stack at 3.1 bar calculated from experimental measurements with Eq.1 (HHV and ρ_N are, respectively, hydrogen high heating value and density in normal conditions and the division by 3600 is necessary because Q is expressed in Nl/h). Since Fig. 6 is composed of more experimental points (affected by measurement errors) the trend seems to be a bit more oscillating. However, it is clear the efficiency decrease trend with current increase due to ohmic losses [29] increase that generates a voltage increase.

$$V_{rev} = V_0 - \frac{R \cdot T}{2 \cdot F} \cdot \ln\left[\left(\frac{1}{\sqrt{p}}\right) \cdot \frac{[H_2] \cdot [O_2]^{1/2}}{[H_2O]}\right] \quad (2)$$

Figure 5

Figure 6 shows the pressure effect on electrolyser stack efficiency. Since the Nernst's potential [29] (Eq.2 for this electrolysis reaction) is increasing with pressure increase and the pressure effect on losses is not too much significant, the efficiency decreases with pressure increase. Moreover, Fig. 6 shows the efficiency decrease with current increase already discussed for Fig. 5.

Figure 6

The results obtained from the experimental data, represented in Fig. 5 and 6, allows determining the performance curves for an alkaline pressurized electrolyser: therefore, they can be implemented in the software W-ECoMP, in order to perform a realistic thermo-economic analysis of the system in time-dependent conditions throughout the year.

4. W-ECoMP software for time-dependent thermo-economic analysis

W-ECoMP is an original software developed by the Thermo-chemical Power Group (TPG), at the University of Genoa [30], for the thermo-economic analysis and optimization of energy systems in time-dependent conditions [31]. It is characterized by a modular approach and a standard component interface, which allows the user to build complex cycle configurations in a short time without modifying the core of the program, maintaining at the same time the flexibility and the extendibility of library components (50 modules are available at the moment). In addition, the analysis of the same plant can be performed considering different economic scenarios [32][33]. One of the most important features of W-ECoMP is the possibility of optimizing the plant at two different hierarchical levels:

- the operating strategy for existing energy systems (low level);
- the size of one or more components during the plant design (high level).

The two hierarchical levels of optimization in W-ECoMP are shown in Fig. 7.

Figure 7

W-ECoMP is provided with cost equations that evaluate the capital cost of the single components of the plant based on the installed power. Cost functions are updated periodically in order to consider the development in performance improvement and market prices as well and allow to calculate the Purchased Equipment Cost (PEC) for each component of the plant.

In the case under analysis, the cost function implemented for the alkaline electrolyser is extrapolated from market data, referred to different producers of alkaline electrolysers worldwide [34], as shown in Fig. 8.

Figure 8

The cost function for pressurized devices is reported below [22]:

$$C_{fix,AECs} = \alpha \cdot 37455 \cdot P_{inst}^{-0.4832} \tag{3}$$

The coefficient α takes into account additional costs for auxiliaries: a conservative value of 1.1 was assumed for α in the present analysis.

The calculation of PEC is performed in one of the three subroutines that describes each module and represents the first step to calculate the Total Capital Investment (TCI). TCI is highly relevant in the economic analysis of a plant [35]; however, the final aim is the calculation of the investment profitability. The most important parameters that describe the profitability of the plant are Net Present Value (NPV) and Discounted Pay Back Period (DPBP), as reported in [22][31][35].

In order to perform the time-dependent thermo-economic optimization of energy systems, taking into proper account the variations in energy demands and renewable energy sources (i.e. solar) availability, the year is divided into an adequate number of representative periods and energy demands are estimated for each period.

The inputs for the software are: (i) energy demands versus time; (ii) renewable energy sources availability vs time; (iii) fuel and energy costs; (iv) component capital costs vs. size; (v) operating and maintenance costs vs. time.

In general, the objective of the optimization procedure is the minimization of an objective function [36]:

- At the low level (*operating optimization*), the size of the components is fixed [36], and the objective function is represented by the variable costs only;
- At the high level (*size optimization*), the size of the components has to be determined and the objective function is represented (the sum of variable and fixed annual costs).

More details about the equations employed for the calculation of the objective function at the different optimization level are reported in previous publications by the authors [22][23][31][32][33].

In both cases, the satisfaction of the energy demands throughout the whole year represents the main constraint of the optimization problem.

4.1 Plant analysis in W-ECoMP

The plant configuration consists of photovoltaic panels for the production of renewable electricity, to feed the alkaline pressurized electrolyser. The high amount of oxygen (8 kg for each kg of H_2) co-produced by water electrolysis process is sold to industrial users. Since renewable electrical energy produced by photovoltaic panels is a time-dependent and not controllable parameter, thus two different scenarios are investigated:

- Scenario 1: the electrolyser is fed only by renewable electricity, when available: in the remaining periods the production is zero;
- Scenario 2: when solar energy production by renewable electricity is not enough, electrical energy is purchased from the national grid, in order to assure a constant H_2 production.

Plant analysis is performed on one year, taking into proper account the time dependent nature of the solar energy. The aim of the study is the thermo-economic optimization of the whole system, determining the best size and management in order to minimize annual costs and obtain the highest revenues [33][35][37][38]. Photovoltaic energy production is influenced by the hour of the day and by the season. For the present analysis, the irradiance curves related to Savona (North Italy) have been considered [39] and the average monthly irradiance values have been inserted in the software, as input: therefore, the analysis has been performed in W-ECoMP considering 12 representative days of the year (an average day per month). Figure 9 shows solar irradiance values for all the representative days of the year. It is worth noting the strong influence of the season: in July (summer day), solar irradiance has a peak of 1200 W/m^2, solar energy is available for 14 hours and energy production is about 6.5 kWh/m^2 day; in March (mid-season day) solar irradiance has a peak of 700 W/m^2, solar energy is available for 11 hours and energy production is about 3.8 kWh/m^2 day; in January (winter day) solar irradiance has a peak of 300 W/m^2, solar energy is available for 9 hours and energy production is about 1.6 kWh/m^2 day.

Figure 9

The Italian economic scenario has been chosen and the following assumptions have been considered:

- **Hydrogen selling price:** high purity hydrogen selling price can vary in a wide range according to the economic scenario [1][32][40]. In the present analysis, a selling price of 4€/kg has been assumed.
- **Oxygen selling price** in the case under analysis is assumed 150 €/ton, which is the minimum selling price for industrial use of oxygen [31].
- **Electrical energy cost** represents a term of primary importance, thus a parametric analysis has been performed in order to investigate its influence on the economic results. The average current market price in Italy is about 50 €/MWh [41]. However, considering that the most of electricity from the grid would be purchased in night hours, when the prices are usually lower, three different energy costs of 30 40 and 50 €/MWh have been considered, evaluating their influence on the results.
- **Plant life** has been assumed equal to 15 years.
- **Inflation rate** in Italy is equal to 0.4%, as reported in [42].
- **Average income tax** in Italy is equal to 22%, as reported in [42].

5. Economic results

The analysis has been performed considering a fixed size of 1 MW of photovoltaic panels installed, with a typical value of electrical efficiency of 17%. Even if more complex models are possible for photovoltaic panels, in this work the energy conversion rate has been maintained constant for all the periods (considering just the mentioned efficiency value), as usually carried out in similar optimization works [33]. All the other aspects are included in the input curves. This simplified approach is usually able to produce reliable results for analyses related to global values, such as calculation of plant size and thermo-economic results. The aim of the thermo-economic analysis is to evaluate the optimal ratio between the size of the photovoltaic plant and the electrolyser, minimizing the value of the Discounted Pay Back Period.

Scenario 1

The first analysis has been performed considering to feed the AEC only with the electricity produced by the solar source, when available; in the remaining periods the device is shut down. Starting from the solar availability curves represented in Fig. 9, for each period of the year, the model calculates the electrical energy outlet as the product of irradiance and installed area, corrected with panel efficiency. The operative equivalent hours are calculated by the software as the ratio between annual electrical energy produced (or consumed in case of the electrolyser) and installed power.

Fig. 10 shows the results of the simulations from the energetic standpoint, considering the number of equivalent hours of the AEC for different sizes: since electrolysers present high investment costs, it would be convenient to have an high number of operative hours, in order to increase revenues from H_2 production and allow for lower DPBP. On the other hand, it is worth remarking that specific investment costs are significantly higher for lower sizes of AECs: as Fig. 8 shows, investment costs are about 2,500 - 3,000 €/kW for small size electrolysers (<100 kW), while they are about 1,500 €/kW for medium-large sizes (500 - 1,000 kW). Fig. 10 shows that small size AECs would present an acceptable number of operative hours (higher than 3,000): however, on account of their high capital cost, they would not represent an acceptable investment; on the other hand, large size AECs would be operative for less than 1,500 hours, therefore they would not represent a worthy solution as well. In this scenario, the analysis performed by W-ECoMP software has shown that DPBP would be higher than 15 years (assumed as plant lifetime) for each size considered, representing a not economically viable solution: the results for this scenario are summarized in Tab. 2. It is worth remarking that electrical operative equivalent hours, shown in Fig. 10, are the ratio between electrical energy and AEC installed power reported in Table 2.

Figure 10

Table 2

Scenario 2

The situation is different considering to purchase electricity from the national electrical grid when solar energy is not available, in order to have the AEC operative all the year continuously, increasing H_2/O_2 production and revenues. Moreover, this solution would allow avoiding frequent on/offs of the device throughout the year, that would decrease AEC lifetime. For each period of the year, the software W-ECoMP compares the electrical input required by the electrolyser and the electrical energy produced by solar panels: when the available energy is lower than the size of the AEC, the difference is purchased from the grid. Fig. 11 shows the DPBP trends for three different electricity prices of 30 40 and 50 €/MWh: the average electricity price in Italy is 50 €/MWh, as reported in [41]; however, since photovoltaic plants work in day hours, when prices are higher, the assumption of considering lower prices, typical of night hours, is realistic. Since AEC life is 15 years, solutions with a DPBP higher than 10 years are considered not profitable. Fig. 11 shows that the most profitable results are obtained for higher AEC sizes, since the capital investment is significantly lower, as reported in Fig. 9; it is worth noting that AEC sizes higher than 200 kW allow acceptable DPBP (lower than 7 years). For smaller sizes (lower than 100 kW), the influence of electricity price becomes more evident: in a low-cost energy scenario (30 €/MWh), the investment would be still profitable, allowing a DPBP lower than 10 years; for higher energy prices (40 - 50 €/MWh), DPBP would be significantly higher: these configurations are not considered economically viable. It is worth noting that the trend of the DPBP is similar to the trend of capital costs of AEC, shown in Fig. 8: this fact confirms that, because of the high capital costs, the best solution is installing a larger AEC, even if the number of operative hours would decrease and the amount of electricity purchased by the national grid would be higher. From the energetic standpoint, it is worth remarking that not the entire amount of H_2 is produced by renewable sources: the percentage of H_2 produced by energy from photovoltaic panels depends on the electrolyser capacity: it is 40% for a 70 kW AEC, 32% for a 200 kW AEC, 28% for a 300 kW AEC, 22% for a 500 kW AEC. Therefore, despite installing a larger AEC guarantees the best economic results in terms of DPBP (Fig. 11), the percentage of H_2 produced by renewable energy decreases.

Figure 11

Figure 12 reports the comparison between TCI and NPV for different electricity prices and for the different sizes of AEC considered. TCI is not affected by electricity cost. For low AEC sizes, NPV is lower than TCI, showing that the investment is not profitable. At higher AEC sizes, NPV is always superior than TCI: the investment is reliable and profitable. It is worth noting the influence of electricity price: considering the 500 kW size, the NPV/TCI ratio is 2 for low energy scenario, decreasing to 1.5 and 1 for medium and high price scenarios. The influence becomes even more evident for higher sizes.

Figure 12

Finally, it is worth considering that economic results, for both the scenarios, are affected by the productivity of photovoltaic panels, which depends on plant location: installing the same plant in Agrigento (Sicily - South Italy), an average increase of about 15% in terms of irradiance is provided, as reported in the Italian solar atlas website [39]. The increase in terms of solar energy production is related to the geographic coordinates of this second location (37°18’39.87”N 13°34’35.57”E) that show a significant lower latitude in comparison with Savona. Therefore, electricity purchasing by national grid and the associated costs are reduced. Thanks to the flexibility of W-ECoMP software, the same plant can be analyzed in different scenarios, comparing the economic results (i.e. for different irradiance or electrical energy costs). Figure 13 reports the DPBP trends for Savona (North Italy) and Sicily (South Italy), for different AEC sizes, considering 50 €/MWh as electricity price; the trends are similar, but installing the same plant in a more favorable location in terms of irradiance allows to obtain most profitable results: in particular, it is worth noting that smaller sizes AECs, not economically viable in Savona scenario, would be feasible in Sicily, where irradiance is higher and electricity purchasing is reduced. From the energetic standpoint, the percentage of H_2 produced by energy from photovoltaic panels is obviously increased: it is 43% for a 70 kW AEC (40% in Savona), 35% for a 200 kW AEC (32% in Savona, 24% for a 500 kW AEC (22% in Savona).

Figure 13

6. Conclusions

This paper aimed to optimize a plant for hydrogen production by a pressurized alkaline electrolyser fed by renewable energy (PV panels), determining the optimal size and management of the system. Since the time-dependent nature of the renewable solar energy, the performance of the system was investigated using the W-ECoMP software for the thermo-economic analysis of energy systems over the year, developed by the Authors research group. The off-design performance curve of the electrolyser installed in the University campus of Savona (Italy) was obtained by the experimental results carried out in the framework of the IDRO-RIN TRAN-GENESI research project and then implemented in W-ECoMP. The main results obtained in this work may be resumed as follows:

- The experimental tests show that electrolyser efficiency increases as the current decreases with an almost linear trend; reducing pressure has a positive influence on efficiency.
- The thermo-economic analysis showed that,using only energy produced by the PV to power AECs, when available, and keeping the machines off for the remaining periods (scenario 1), is a not economically viable solutions for the high investment costs of the AEC and the low number of operative hours (about 2,400 hours per year).
- On the other hand, considering to purchase electricity from the grid when solar energy is not sufficient (scenario 2), good results are obtained, in terms of both DPBP and NPV, for large size (⩾200 kW) electrolysers.
- Since the specific investment costs of the electrolyser is higher for small sizes, the best economic results had been obtained for 800 kW size; in a low electricity cost scenario (30 €/MWh), DPBP is about 5 years and NPV to TCI ratio is equal to 2, which represents a worthy result. It is worth noting that, since the nature of solar energy, most of the electrical energy is purchased by National grid in night hours, when market prices are typically lower: taking into proper account this aspect, specific energy contracts may be signed with the National government, allowing for a lower price for electrical energy purchasing.

These results show a good potential for hydrogen generation from renewable sources: in particular, considering coupling PV panels and an alkaline electrolyser, the results show the importance of evaluating the best size of the two systems, considering carefully the influence of the scenario, in terms of both electrical energy cost and operative hours for the solar panels. Finally, it is worth noting that the present thermo-economic approach can be employed for sizing similar systems located in other scenarios, considering different irradiance solar curves and the integration of the components with other renewable generators as well (i.e. hydroelectric plants, wind turbines).

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8. References

[1] Marban G., Valdés-Solis T., Towards Hydrogen economy?. International Journal of Hydrogen Energy, 2007 (32), 1627-1635.

[2] Briguglio N. et al., Renewable energy for hydrogen production and sustainable urban mobility, International Journal of Hydrogen Energy. 35 (2010) 9996 – 10003.

[3] De Jong P., Sánchez A.S., Esquerre K., Kalid R.A., Torres E.A., Solar and wind energy production in relation to the electricity load curve and hydroelectricity in the northeast region of Brazil. Renewable and Sustainable Energy Reviews 23 (2013) 526–535.

[4] Ferrari M.L., Advanced control approach for hybrid systems based on solid oxide fuel cells. Applied Energy, 145 (2015) 364-373.

[5] Barbosa R., Sanchez V.M., Escobar B., Cruz J.C., Toral-Cruz H., Sizing of a solar-hydrogen power source for a portable emergency communication system: Case study of hurricanes in Cancun, Mexico. International Journal of Hydrogen Energy, 40 (2015) 17361–17370.

[6] Motalleb M., Đukic A., Firak M., Solar hydrogen power system for isolated passive house. International Journal of Hydrogen Energy, 40 (2015) 16001–16009.

[7] Khalinejiad A., Riahy G.H., A hybrid wind-PV system performance investigation for the purpose of maximum hydrogen production and storage using advanced alkaline electrolyzer. Energy Conversion and Management, 80 (2014) 398–406.

[8] Pattra S., Sittijunda S., Optimization of Factors Affecting Acid Hydrolysis of Water Hyacinth Stem (*Eichhornia Crassipes*) for Bio-Hydrogen Production. Energy Procedia, 79 (2015) 833-837.

[9] Wu W., Veni I.C., Shin-An C., Jenn-Jiang H., Design and techno-economic optimization of a stand-alone PV (photovoltaic)/FC (fuel cell)/battery hybrid power system connected to a wastewater-to-hydrogen processor. Energy, 84 (2015) 462-472.

[10] Editorial, Optimization methods in renewable energy systems design. Renewable Energy, 87 (2016) 835-836.

[11] Bazmi A.A., Zahedi G., Sustainable energy systems: Role of optimization modeling techniques in power generation and supply - A review, Renewable and Sustainable Energy Reviews, 15 (2011) 3480-3500.

[12] F. El-Shatter Thanaa, N. Eskander Mona, T. El-Hagry Mohsen, Energy flow and management of a hybrid wind/PV/fuel cell generation system, Energy Conversion and Management, 47 (2006) 1264-1280.

[13] Shariatzadeh O.J., Refahi A.H., Abolhassani S.S., Rahmani M., Modeling and optimization of a novel solar chimney cogeneration power plant combined with solid oxide electrolysis/fuel cell. Energy Conversion and Management. 15 (2015) 223-232.

[14] Ahmadi P., Dincer I., Rosen M.A., Thermodynamic modeling and multi-objective evolutionary-based optimization of a new multigeneration energy system. Energy Conversion and Management. 76 (2013) 208-300.

[15] GSE (Gestore Servizi Energetici), "Rapporto Statistico 2013 Impianti a fonti rinnovabili" http://www.gse.it/home last access 30/11/2015.

[16] Sallaberry F., Pujol-Nadal R., Larcher M., Rittmann-Frank M.H., Direct tracking error characterization on a single-axis solar tracker. Energy Conversion and Management, 105 (2015) 1281-1290.
[17] Gan L.K., Shek J.K.H., Mueller M.A, Hybrid wind-photovoltaic-diesel-battery system sizing tool development using empirical approach, life-cycle cost and performance analysis: A case study in Scotland. Energy Conversion and Management, 106 (2015) 479-494.
[18] http://www.mcphy.com/en/products/electrolyzers/small-and-medium-units/, last access on the 19th February 2016.
[19] Garrigós A., Lizán J.L., Blanes J.M., Gutiérrez R., Combined maximum power point tracking and output current control for a photovoltaic-electrolyser DC/DC converter. International Journal of Hydrogen Energy, 39 (2014) 20907–20919.
[20] Ferrari M.L., Pascenti M., Traverso A.N., Massardo A.F., Hybrid System Test Rig: Chemical Composition Emulation With Steam Injection, Applied Energy, 97 (2012) 809–815.
[21] Ferrari M.L., Massardo A.F., Cathode-Anode Interaction in SOFC Hybrid Systems. Applied Energy, 105 (2013) 369–379.
[22] Bellotti D., Rivarolo M., Magistri L., Massardo A.F., "Thermo-economic comparison of hydrogen and hydro-methane produced from hydroelectric energy for land transportation". International Journal of Hydrogen Energy, 40 (2015) 2433-2444.
[23] Rivarolo M., Massardo A.F., Optimization of large scale bio-methane generation integrating “spilled” hydraulic energy and pressurized oxygen blown biomass gasification. International Journal of Hydrogen Energy, 38 (2013) 4986-4996.
[24] Ferrari M.L., Traverso A., Pascenti M., Massardo A.F., Plant management tools tested with a small-scale distributed generation laboratory. Energy Conversion and Management, 78 (2014) 105-113.
[25] Ferrari M.L., Pascenti M., Sorce A., Traverso A., Massardo A.F., Real-time tool for management of smart polygeneration grids including thermal energy storage. Applied Energy, 130 (2014) 670-678.
[26] Posso F., Zambrano J., Estimation of electrolytic hydrogen production potential in Venezuela from renewable energies. International Journal of Hydrogen Energy, 39 (2014) 11846-11853.
[27] Gahleitner G., Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications. International Journal of Hydrogen Energy, 38 (2013) 2039-2061.
[28] Escobar B., Hernández J., Barbosa R., Verde-Gómez Y., Analytical model as a tool for the sizing of a hydrogen production system based on renewable energy: The Mexican Caribbean as a case of study. International Journal of Hydrogen Energy, 38 (2013) 12562-12569.
[29] Orna M.V., Stock J., Electrochemistry, past and present. American Chemical Society, Columbus (OH), ISBN 0-8412-1572-3.
[30] www.tpg.unige.it, last access on the 19th February 2016.
[31] Rivarolo M., Bellotti D., Mendieta A., Massardo A.F., “Hydro-methane and methanol combined production from hydroelectricity and biomass: Thermo-economic analysis in Paraguay”, Energy Conversion and Management, 2014 (79), 74-84.
[32] Rivarolo M., Bogarin J., Magistri L., Massardo A.F., 2012, “Time-dependent optimization of a large hydrogen generation plant using “spilled” water at Itaipu 14 GW hydraulic plant”, International Journal of Hydrogen Energy, 2012 (37), pp 5434-5443.
[33] Rivarolo M., Greco A., Massardo A.F., “The thermo-economic optimization of the impact of renewable generators on poly-generation smart grids including hot thermal storage”, Energy Conversion and Management, 2013 (65), 75-83.
[34] Jensen J.O., Bandur V., Bjerrum N. J., Jensen S.O., Ebbesen S., Mogensen M., Tophøj N., Yde L., 2006, “Pre investigation of water electrolysis”, PSO-F&U 2006-1-6287.
[35] Bejan A., Tsatsaronis G., Moran M., 1996, “Thermal design and optimisation”, Interscience Publication, John Wiley & Sons Inc.
[36] Yokohama R., Ito K., 2006, “Optimal design of gas turbine cogeneration plants in consideration of discreteness of equipment capabilities”, Journal of Engineering for Gas Turbines and Power, 128 (2006) 336-343.
[37] Garret Vanderplaats N., "Numerical Optimization Techniques for Engineering Design", McGraw-Hill Publishing Company.
[38] Fakehi A.H., Ahmadi S., Mirghaed M.R., Optimization of operating parameters in a hybrid wind-hydrogen system using energy and exergy analysis: Modeling and case study. Energy Conversion and Management 106 (2015) 1318-1326.
[39] www.solaritaly.enea.it last access on 31/01/2015.
[40] Godoy GAR. Itaipu hydroelectric power plant turbinable energy use in hydrogen buses: case study in Foz do Iguacu city. Brazil: Universidade Estadual de Campinas. Faculdade de Engenharia Mecânica, http://cutter.unicamp.br/document/?code¼vtls000447162; 2008.
[41] www.mercatoelettrico.org, last access on the 10th March 2015.
[42] www.tradingeconomics.com, last access on the 10th March 2015.

9. Figures and captions

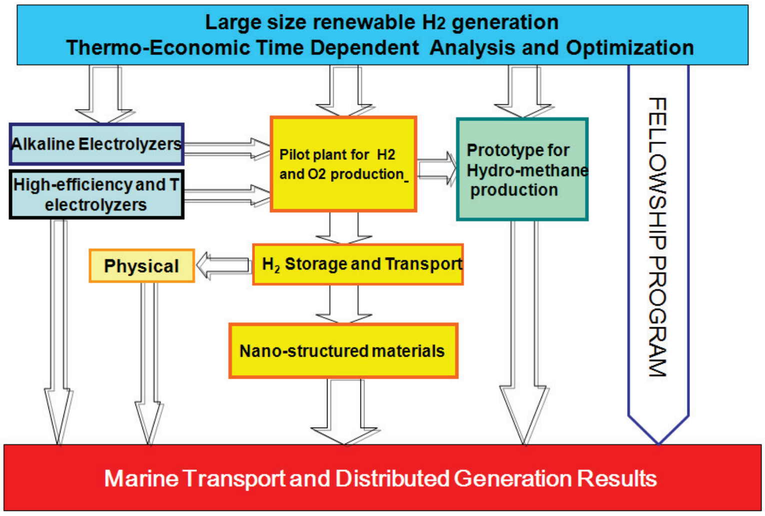

Figure 1: IDRO-RIN TRAN-GENESI project: main topics.

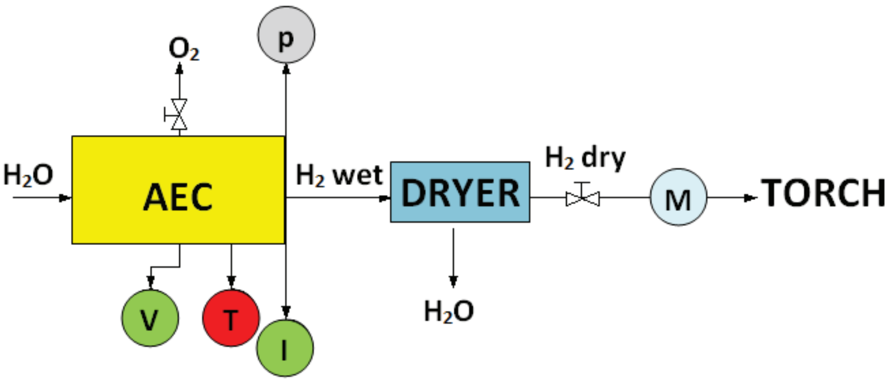

Figure 2: Plant layout.

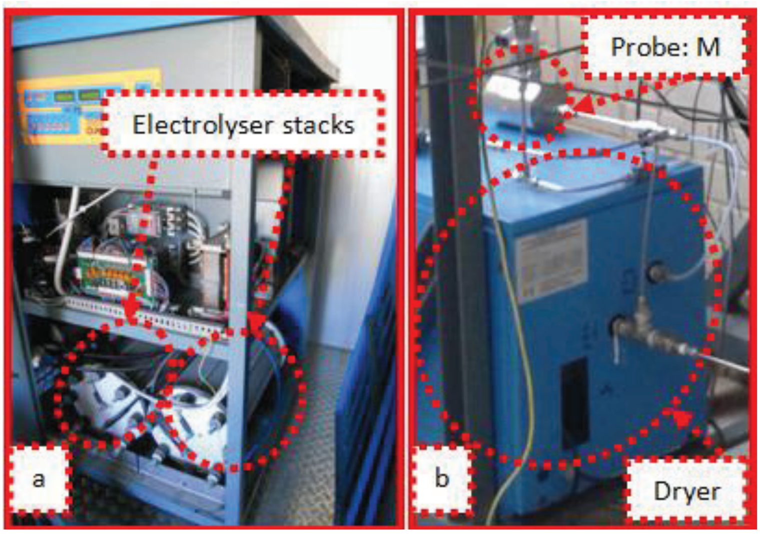

Figure 3: Picture of the electrolyser (a) and some external components installed for measurement reasons (b).

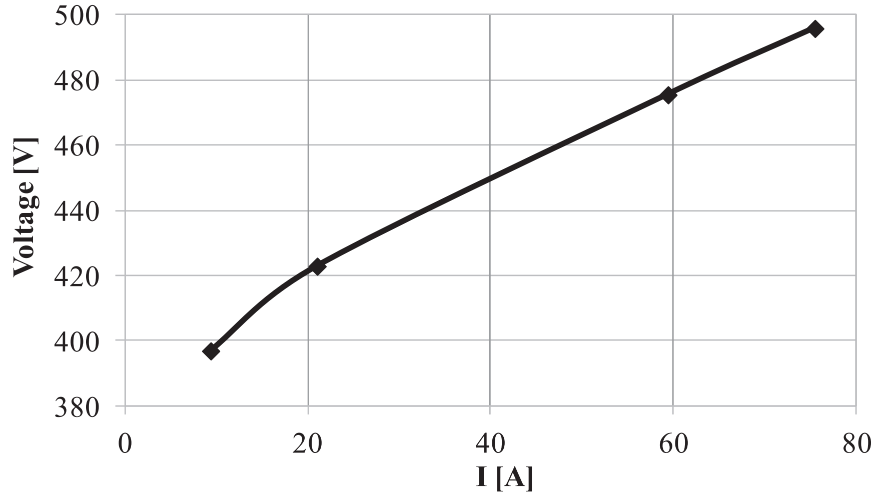

Figure 4: Constant pressure (p = 2.4 bar) characteristic curve of the electrolyser stack.

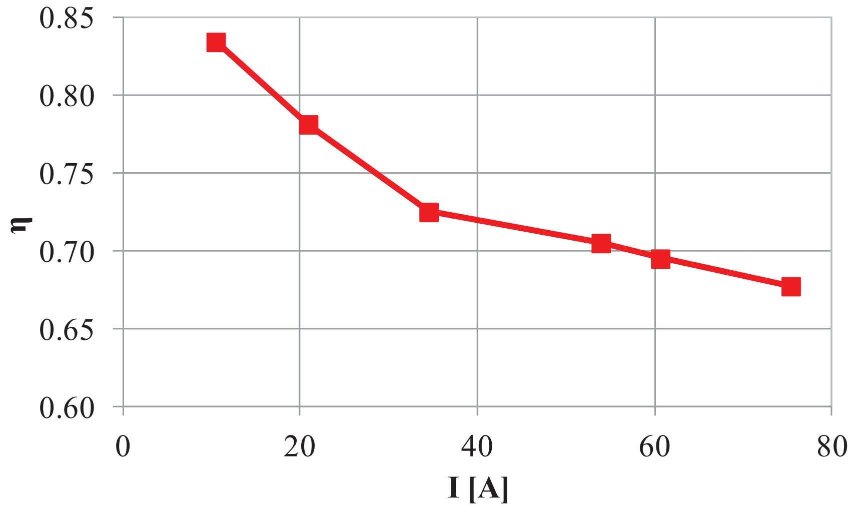

Figure 5: Constant pressure (p = 3.1 bar) efficiency of the electrolyser stack.

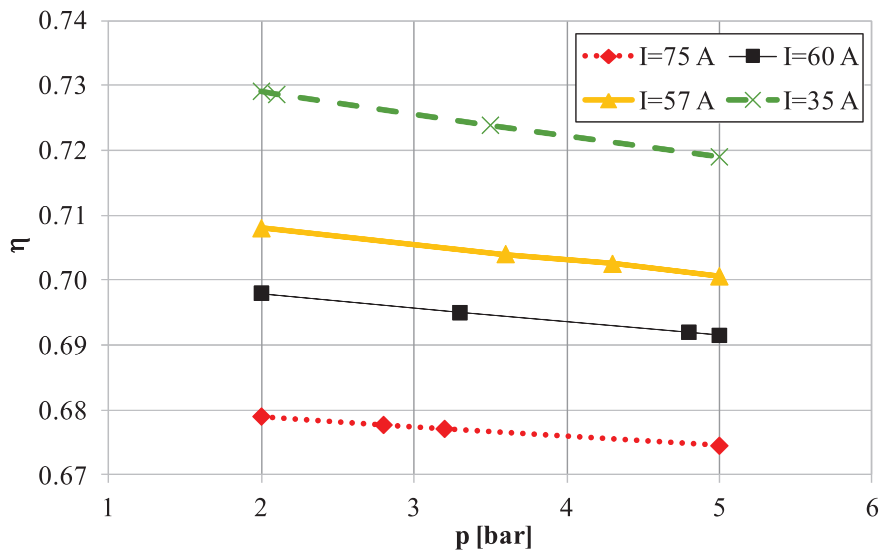

Figure 6: Efficiency of the electrolyser stack: pressure influence.

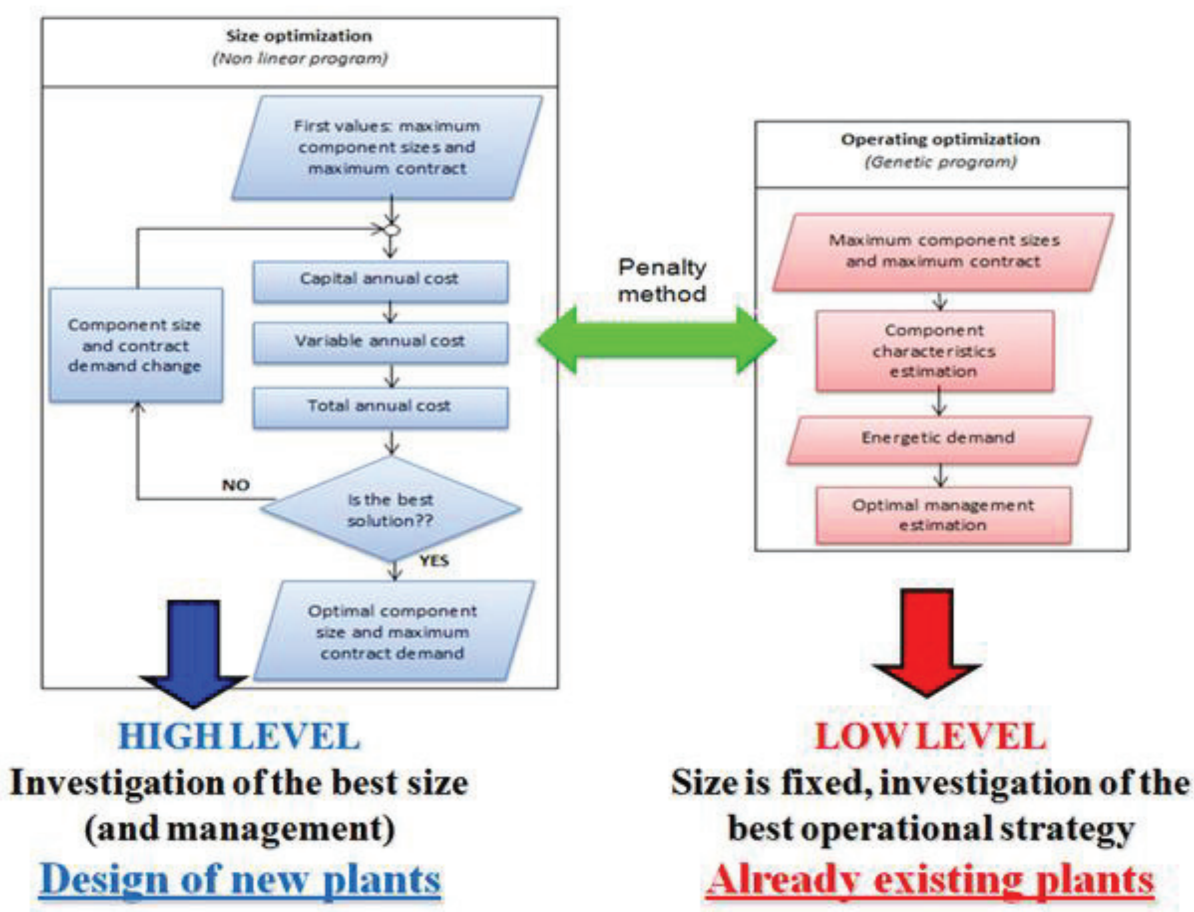

Figure 7: Optimization strategies implemented in W-ECoMP [30].

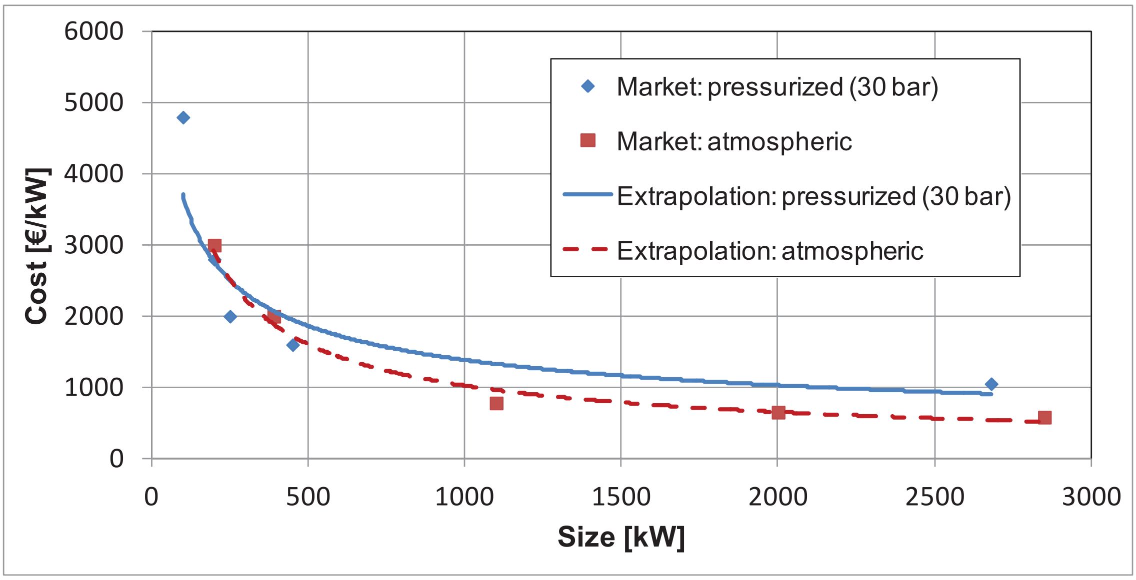

Figure 8: Cost function for commercial alkaline electrolysers [34].

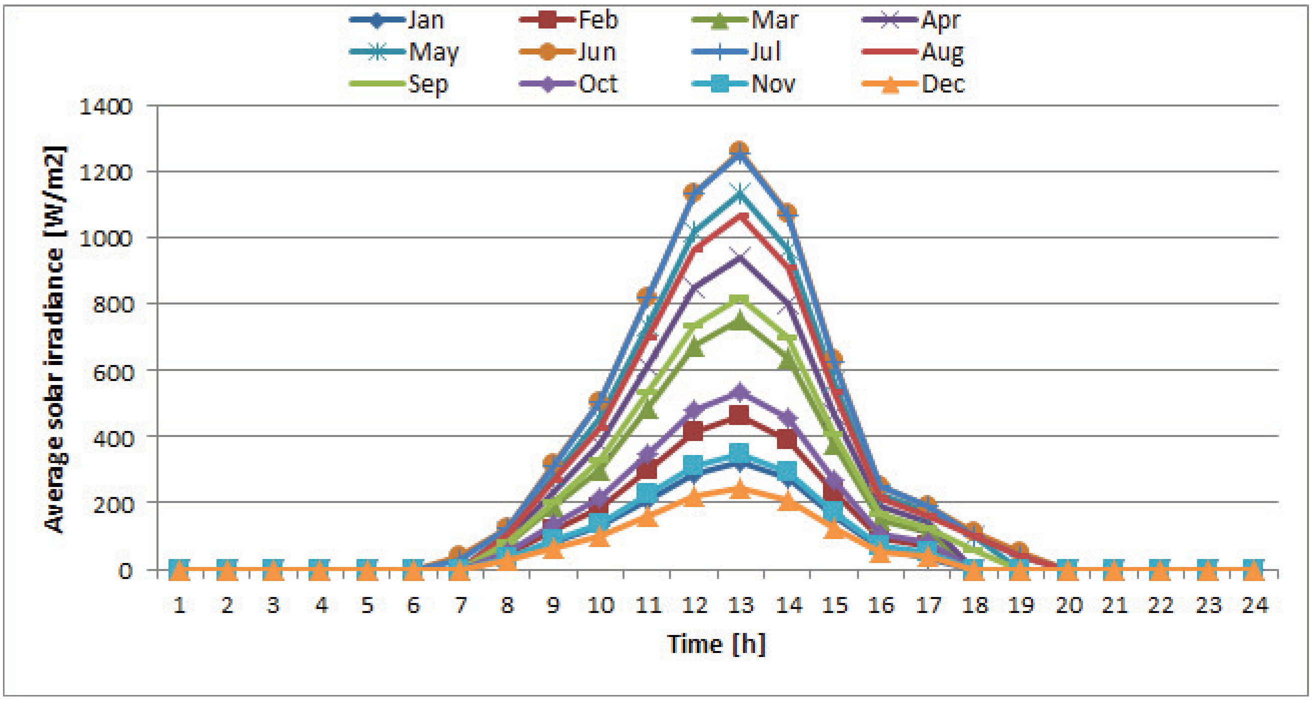

Figure 9: Solar irradiance curves for some representative days (Savona, Italy).

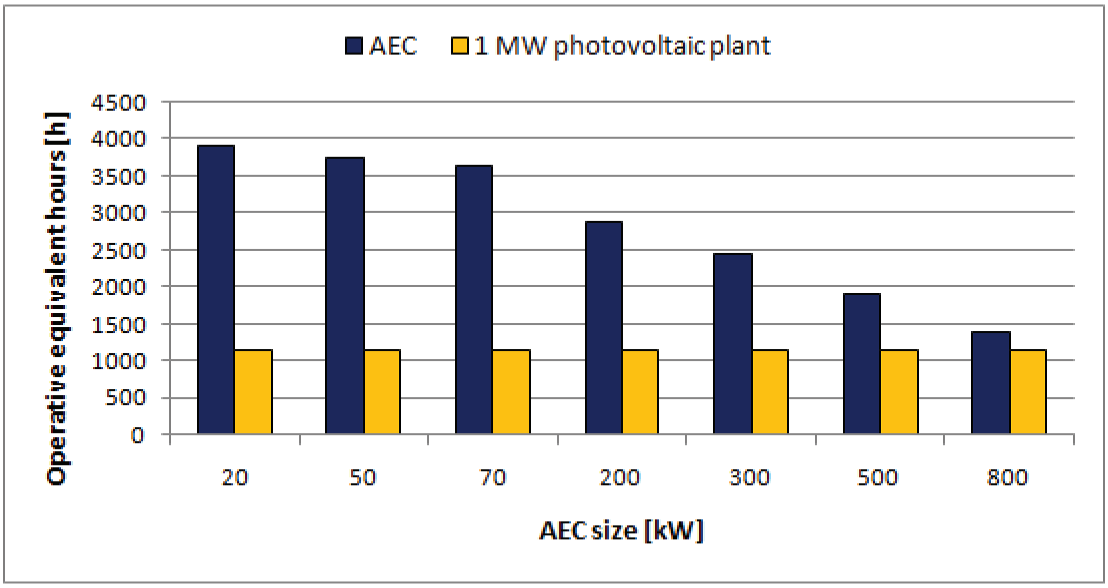

Figure 10: Operative equivalent hours for different AEC sizes.

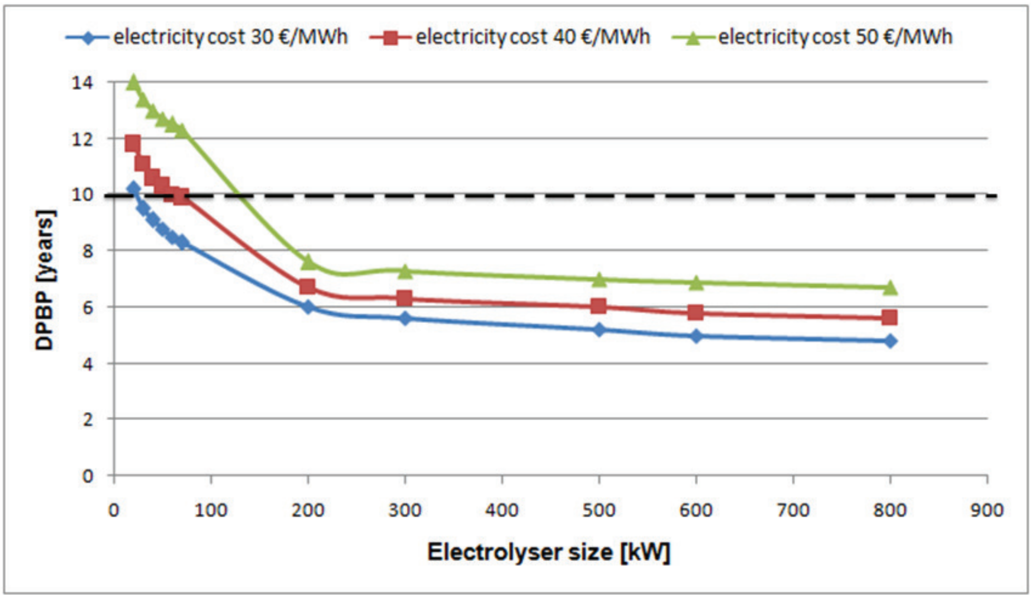

Figure 11: DPBP vs electrolyser size for different electrical energy costs.

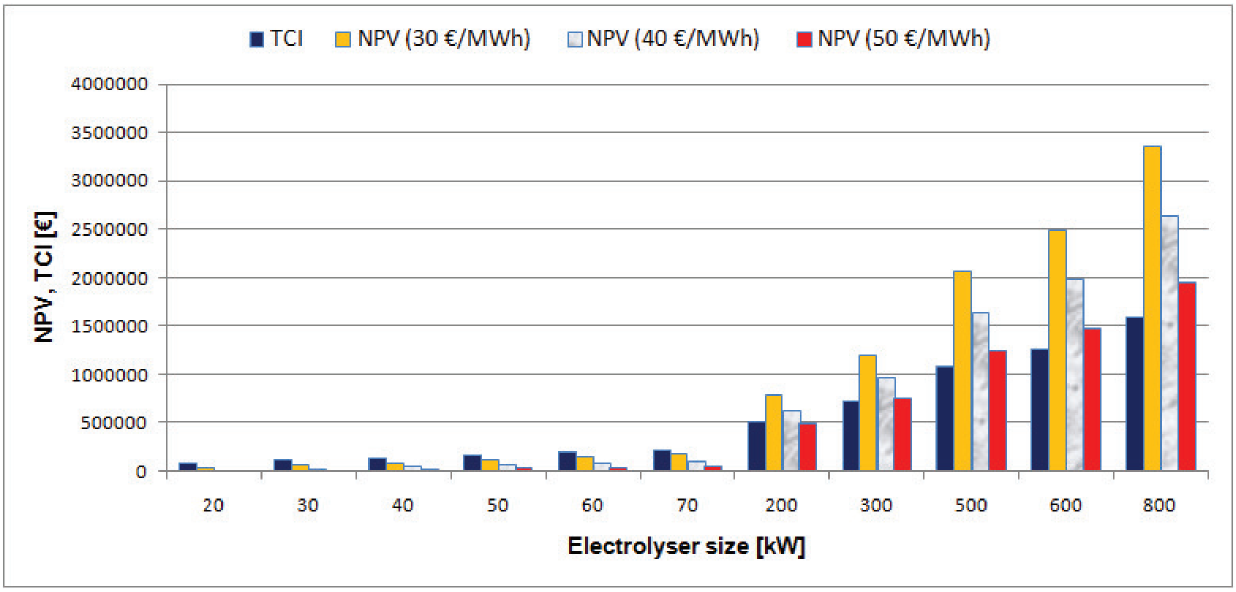

Figure 12: TCI and NPV vs electrolyser size for different electrical energy prices.

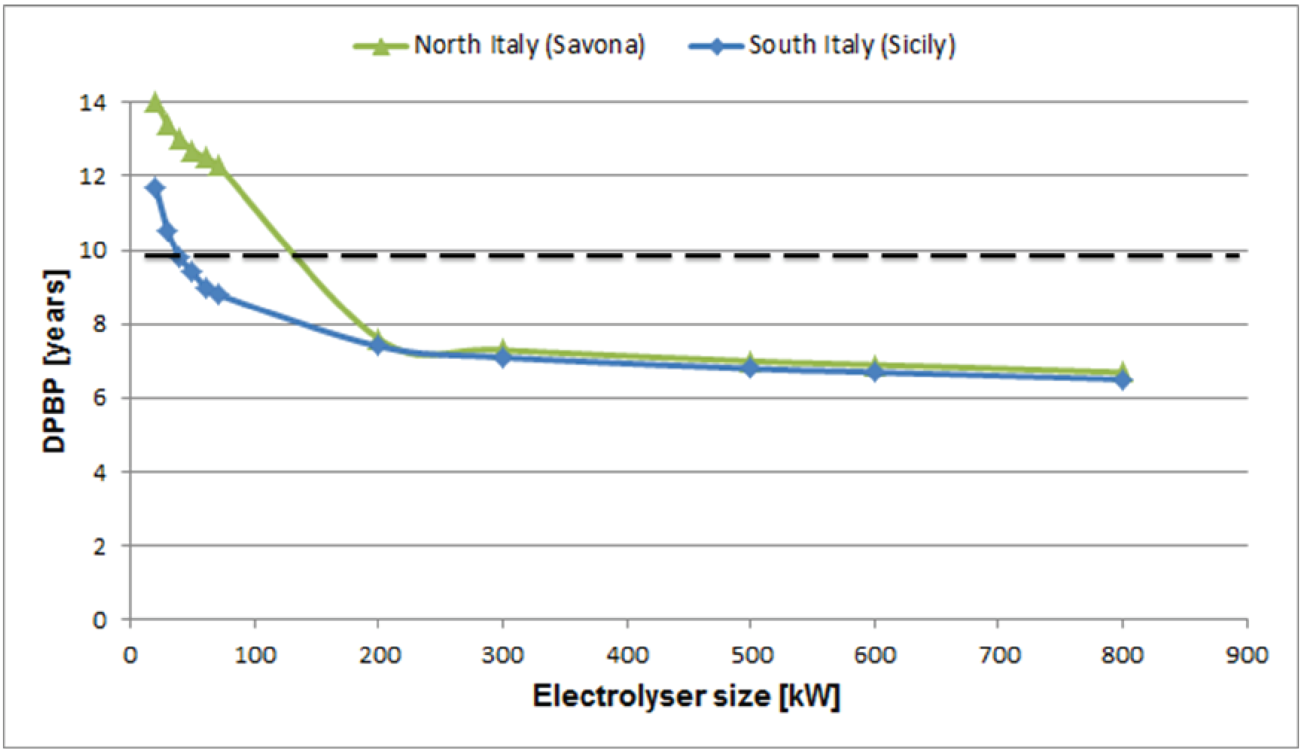

Figure 13: DPBP vs electrolyser size for different climates (North and South Italy).

Table 1

Table 1: Main technical data for Piel "DODICIMILA" electrolyser [18].

Property	Value
Operative pressure (relative)	1.9-4 bar
Ambient temperature	5-35°C (278.15-308.15 K)
Gas pureness	99.5%
Nominal hydrogen flow rate	8000 Nl/h
Nominal oxygen flow rate	4000 Nl/h
Nominal consumed electrical power	42 kW
Nominal water consumption	6.4 l/h
Weight	870 kg

Table 2

Table 2: Energetic and economic results (scenario 1).

Installed power [kW]	Solar energy to AEC [kWh/year]	H_2 production [kg/year]	TCI [€]	DPBP [years]
20	78,000	1,480	78,000	> 15
50	187,660	3,570	166,000	> 15
70	254,110	4,830	218,000	> 15
200	575,940	10,940	513,000	> 15
300	735,970	13,980	714,000	> 15
500	947,330	18,000	1,083,000	> 15
800	1,102,940	20,960	1,589,000	> 15